Trial Report of Localization for Visual Based Tracking System in Asteroid Flyby

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Flyby imaging has attracted attention as a method of small body exploration. The visual-based tracking system has been widely used to obtain high-quality images. The high relative velocity between the spacecraft and asteroid makes it difficult to track the target asteroid completely around the closest approach point. The uncertainties of the measured relative parameter cause uncertainties in the required control trajectory profiles for the asteroid tracking. This study proposes a two-degree-of-freedom control system considering the relative parameter uncertainties. In particular, this study performs localization, that is, relative position estimation between the spacecraft and asteroid. A particle filter is applied to the estimator, and its applicability and limitations are discussed through a numerical simulation of a case study.

Keywords: flyby, imaging, visual based tracking

1. Introduction

Flyby is one of the methods of small bodies exploration and a spacecraft acquires various information while passing near the target body. Target tracking imaging is one of the most popular observations. The tracking system consists of a camera, active scan mirror, and its driver. The required tracking profile for the mirror is calculated by utilizing the target position in the imager and a geometrically defined relative position. However, at the point of closest approach between the small body and the spacecraft, the target angular velocity in the direction of the body becomes sharply change, so it is difficult to completely follow the center of the body only by feedback from obtained images⁽¹⁾. Moreover, the relative parameter uncertainties between the small body and spacecraft cause uncertainties in the required mirror profiles for tracking. This study aims to design a suitable trajectory and robust control system that reduces the tracking errors under constraints and uncertainties. Especially, this article shows the proposed control system concept and performs a trial for localization which reduces the uncertainties.

2. Geometionally Definition

This article assumes the coplanar model that the asteroid and spacecraft trajectories are in the same orbital plane⁽²⁾. It is assumed that the relative trajectory of the spacecraft and asteroid near the closest approach point can be described as the linearized model with a constant relative velocity in the small body-fixed coordinate system because of the low

Fig. 1. Geometrical definition of the spacecraft sight direction during the flyby

gravity effect and high-speed flyby as Fig. 1. The origin of the coordinate system is defined as the spacecraft's closest approach point to the asteroid. Its relative distance is H [km] and time is $t = 0$ s. The relative velocity of the spacecraft to the asteroid is V [km/s]. The required direction angle of the asteroid from the spacecraft's line of sight to achieve the tracking is θ_r [rad]. The active scan mirror angle from the spacecraft's line of sight is θ [rad]. The positional error of asteroid center from imager screen center is y_e [mm]. The misalignment angle between the active scan mirror line of sight and asteroid center is $\Delta\theta$ [rad].

3. Concept of Visual Based Tracking System

The two-degree-of-freedom control system considering the relative parameter uncertainties is proposed as Fig. 2.

3.1 State Equation The state equation of the active scan mirror is expressed by Eqs. (1) and (2). Here, J is the moment of inertia of the mirror, and u is the torque input applied to the mirror.

$$\dot{x} = Ax + bu = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \theta \\ \dot{\theta} \end{pmatrix} + \begin{pmatrix} 0 \\ 1/J \end{pmatrix} u \dots \dots \dots (1)$$

Fig. 2. Block diagram of the proposed system

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$$y = cx = \begin{pmatrix} 1 & 0 \end{pmatrix} x \dots\dots\dots (2)$$

3.2 Estimation of the Misalignment Angle and Angular Velocity The misalignment angle $\Delta\theta$ and its angular velocity $\Delta\dot{\theta}$ are estimated from the measurement y_e , considering the orbital motion and imager properties. Here, the transformation matrix from the coordinate system in Sec. 2 to the imager screen coordinate system is also taking into account.

3.3 Feedback Control A feedback input u_e is calculated based on the image obtained from the camera. It uses the misalignment angle $\Delta\theta$ and its angular velocity $\Delta\dot{\theta}$ between the active scan mirror's line of sight and the asteroid. The measurement is performed in discrete-time system. They can be calculated from Eq. (5) using y_e obtained from the camera image.

$$\Delta\theta = \tan^{-1}(y_e/f) \dots\dots\dots (3)$$

$$\Delta\dot{\theta} = \{\Delta\theta(k) - \Delta\theta(k-1)\}/dt \dots\dots\dots (4)$$

$$u_e = -F_b x_e = -(F_{b1} \ F_{b2}) \begin{pmatrix} \Delta\theta & \Delta\dot{\theta} \end{pmatrix}^T \dots\dots\dots (5)$$

Here, k is the number of sample, f is the focal length of the camera, and F_b is the feedback gain vector, designed by the optimal regulator.

3.4 Feedforward Control The feedforward profile is generated considering the parameter uncertainties, hardware's tracking performance, and the predefined acceptable errors. The proposed controller generates the target reference r and feedforward input u_r that minimizes the errors even near the closest approach point. The proposed methods consist of the following sequences. 1) Estimate relative position $\hat{X}(k)$ between the spacecraft and asteroid using camera image, 2) Predict future relative position between the spacecraft and asteroid $\hat{X}(k+1, k+2, \dots)$, 3) Generate target reference r for θ based on the predicted $\hat{X}(k+1, k+2, \dots)$, and 4) Generate feedforward input u_r based on target reference r . This article focuses on the relative position estimation.

4. Localization using Particle Filter

This article performs trial of the localization with the particle filter⁽³⁾, which is the state estimation method by expressing a state candidate with a large number of particles including noise, moving the particle with a transient model and calculating the weight of each particle based on the observations. The relative position between the spacecraft and asteroid is estimated by this filter. The authors expect to apply the particle distribution as the parameter uncertainties effects of the system modeling without the detailed error source modeling. The proposed method is verified through numerical simulations. The preliminary predicted relative trajectory with estimation errors is obtained based on communication with the earth and optical information. The camera information is utilized to calibrate the information. The relative position $\hat{X}(k) = (\hat{X}(k) \ \hat{Y}(k))^T$ estimation sequences are described as follows:

4.1 Observation Calculate the distance D between the spacecraft and asteroid from the center position and size of the asteroid on the screen as $y_{t+1} = D$. The D is a function of the constants V and H from the geometrical constraints.

4.2 Estimation and Updating Weight At first, the particles are moved based on the transient model of the

Fig. 3. Localization simulation results

spacecraft. Then, i -th particle's probability is calculated based on the likelihood function by using observation data and the normalized weights q are updated as Eqs. (6) and (7). This study uses a Gaussian function as the likelihood function and w is the system noise.

$$x_{t+1}^{(i)} = x_t^{(i)} + \begin{pmatrix} V\Delta t & 0 \end{pmatrix}^T + w \dots\dots\dots (6)$$

$$q_{t+1}^{(i)} = q_t^{(i)} p(y_{t+1}|x_{t+1}^{(i)}) \dots\dots\dots (7)$$

4.3 Resampling The particles are rearranged according to the weight of each particle.

4.4 Relative Position Estimation The relative position of the spacecraft and asteroid is estimated by using the expected value as the final estimate as $\hat{X}(k) = x_{t+1} \bar{q}_{t+1}$ by using the averaged weight after the resampling $\bar{q}$.

4.5 Numerical Simulation of Localization This section performs the numerical simulation. Here, H is set as 500 km and V is set as 33 km/s. The asteroid diameter is set as 5.1 km. Initial relative position is set as $X_0 = (-1000 \ 0)$ km and its estimation is $\hat{X}_0 = (-1000 \ 10)$ km. Initial estimation error comes from Okada *et al.*⁽⁴⁾. The results are summarized in Fig. 3. These figures show the time series histories of relative position of the spacecraft and asteroid, and the upper left number shows the order of the sequences. The solid line represents the true value, the dashed line represents the estimate, and the circles are particles. The results confirmed the estimation error was reduced as approaching the closest approach point and it converges about 0.4 km around ± 10 km of the closest approach point. The estimation accuracy is acceptable for the control in this case; however, the results have irreproducible uncertainties, and this aspect might affect the estimation and control results.

5. Conclusion

This article proposes a concept of a control system for asteroid tracking imaging during the flyby. Especially, this article focuses on the relative position estimation system and performs a numerical trial with particle filter. The estimation results are used as a part of the feedforward controller. The effectiveness of the proposed methods has confirmed through a case study's numerical simulation.

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